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EROSIVE EFFECTS OF VARIOUS PURE AND COMBUSTION-
GENERATED GASES ON METALS, PART I

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This study presents an experimental investigation of the thermal and chemical erosion characteristics of steel alloys under the short exposure of high pressure and high temperature propellant gases (vented-combustor apparatus) and pure gases (ballistic compressor apparatus). In the vented-combustor tests, the erosion experienced by the alloys is shown to increase with decreasing thermal conductivity and specific heat. The established linear dependence of mass eroded on number of firings suggests that any

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20.   Abstract - continued

physical alterations undergone by the eroded surface do not
influence future erosion tests. Most significantly, erosion
results of the steel alloys (of widely differing compositions) in
the ballistic compressor show no distinct difference. The explana-
tion for this lack of dependence on metal composition is the
subject of a continuing study. With the exception of the oxygen-
containing gases (i.e., air, O_2/N_2 mixtures) and H_2, the mass
removal experienced by the steel alloys under the action of N_2,
CO, CO_2/A and $N_2/H_2/O_2$ mixtures was very small ($\sim$ 0.25 mg).
The erosion of the steel alloy AISI 4340 was found to increase
linearly with the mole fraction of O_2 in O_2/N_2 mixtures. The
results clearly demonstrate that surface reactions play a
dominant role and that erosion is more than simple melting and
wipe-off.

SUMMARY

This study presents an experimental investigation of the thermal and chemical erosion characteristics of three steel alloys (AISI 1020 carbon steel, AISI 304 stainless steel, and AISI 4340 chrome-moly steel) using as the hot gas source for convective heating, a vented-combustor and a ballistic compressor apparatus. The controlling mechanism of the erosion of steel alloys under the action of high pressure and high temperature propellant gases, in short duration experiments (2 - 4 msec), is the chemical inter-action of the hot propellant gases with the surface of the test specimens. This is in contrast with past investigations utilizing long firing cycles (>20 msec). The relative erosivity of the alloys is shown to depend on their thermal properties. The lower the thermal conductivity and specific heat of the alloy the higher its mass erosion. The established linear dependence of mass removal on number of firings (up to 20 shots) suggested that any physical or chemical alterations undergone by the eroded surface do not influence future erosion tests. Higher erosion occurs in one-dimensional slab configuration than in a circular hole. The heat dissipated in the interior of the specimen is lower for the 1-D slab than the circular hole. The effect of sulphur on the erosion of steel alloys was found to depend on the pressure level of the test. At high peak pressures (>2.7 kbar) the addition of 1% sulphur in the IMR 4198 propellant was found to decrease erosion, whereas at low peak pressures it increased erosion.

The ballistic compressor was used to study the erosive action of individual pure gases on steel alloys. It offers the unique ability to study the erosive action of individual gases on steel alloys and it also enables one to determine the extent of chemical interaction by comparing the erosion results with those obtained using inert gases. Comparison of the erosion results obtained using air and O_2/N_2 mixtures with the N_2 results showed that the erosion of steel alloys by oxygen-containing gases is controlled by the surface reactions between oxygen and iron and, in fact, linearly increases with increasing O_2 concentration. This result clearly

demonstrates that surface reactions are dominant and that erosion is more than simple melting and wipe off. Another very significant finding is that the three alloys, although they differ greatly in composition, erode at nearly the same rate under a given O_2/N_2 concentration. The increased erosion due to the action of H_2 (in comparison to N_2) was attributed to the high diffusivity of H_2 which increases the surface heat transfer coefficient. The possibility, however, of H_2 chemically attacking the solid surface still remains. The low erosive action of CO, CO_2/A and H_2O/N_2 test gases did not allow for qualitative conclusions with respect to their interaction with the steel alloys. Additional diagnostic tests of the eroded surface such as x-ray diffraction techniques and Auger spectroscopy are needed.

Finally, a critical study of the available techniques to measure small surface mass removals ($2 - 20\mu$) has been made. The methods considered were: (1) Weight-loss measurements using ultra-high sensitive balance, (2) Gas-flow through enlarged drilled orifices, and (3) surface loss measurement by nuclear reaction methods. The nuclear methods (diffused oxygen detection and tagged constituents detection) were found to have very attractive potentials.

FOREWORD

The project summarized in this report was carried out under Contract DAAG46-72-C-0078 and administered by the Research Sciences Division, Basic Research Laboratories, of the U.S. Army Materials and Mechanics Research Center, Watertown, Mass. The Technical Monitor was Dr. J. Warren Johnson.

Part II of this report will summarize the results of the continuing studies under Contract DAAG46-72-C-0078 and should be available by the middle of 1976.

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I.   INTRODUCTION

This report summarizes the work conducted at Princeton University over a ten-month period of research, to develop new techniques for investigating the erosion of steel alloy liners and to conduct exploratory investigations with these techniques and with standard methods. The emphasis throughout this investigation was directed toward studying the thermal and chemical aspects (rather than mechanical) of erosion of steel alloys by high pressure and high temperature gases.

The two leading hypotheses on the mechanism of erosion of steel alloys are: (1) the melt-and-wipe-off mechanism based on the premise that erosion occurs due to inert heating and melting of the surface of the test specimen, with subsequent removal of the melt by the aerodynamic forces of the flow, and (2) the chemical mechanism based on the premise that erosion is due to the chemical interaction between the propellant gases and the solid surface. Because of the complex nature of the chemical interactions between high pressure and high temperature multi-component propellant gases with steel alloys, however, investigations of the chemical erosion of steel alloys have been limited. Up to now, explanations of the erosive action of these gases were mainly based on the thermal aspects (e.g., melt-and-wipe-off mechanism) with little, if any, reference to the chemical interactions. However, it has not been established that the governing mechanism of the erosion of gun barrels is solely due to inert erosion. Furthermore, the observed chemical alterations undergone by the eroded bore surfaces of fired gun barrels strongly indicate the chemical attack experienced by the steel structure.

The ballistic compressor is a versatile tool for studying the chemical nature of the erosion of steel alloys by high pressure and high temperature gases. The development of the ballistic compressor as a tool for aluminum erosion studies was achieved under the U.S. Army Contract DAAG46-72-C-0078 with Princeton University. The ballistic compressor provides unique capabilities to study, separately, the chemical interactions between metal

alloys and the individual gases at high pressure and high tempera-
ture that constitute the multi-component propellant combustion
products mixture.

In addition to utilizing the ballistic compressor, erosion
tests were performed using the vented-combustor erosion apparatus.
These tests provided information on the cumulative effect of the
propellant gases on the erosion of steel alloys.

In Section II a review of the past investigations on the
erosion of steel vents is presented. The erosive effects of
propellant gases on steel alloys is discussed in Section III.
The tests were performed on three steel alloys, AISI 1020 carbon
steel, AISI 304 stainless steel, and AISI 4340 chrome-moly steel,
using IMR-4198 powder propellant. Comparison tests have also
been performed using Ml and WC 846 propellants. A limited number
of tests have been conducted to investigate the effect of sulphur
added to the propellant on the erosion of steel alloys.

In Section IV, the erosive action of pure gases on steel
alloys is presented. Erosion experiments on the three test alloys
were performed using the following pure gases and pure gas
mixtures: N_2, H_2, CO, CO_2/A, N_2/O_2 and $N_2/H_2/O_2$.

In Section V methods to measure the erosion of steel alloys
are discussed. These methods include gravimetric method, gas
flow technique, and two nuclear reaction techniques.

Finally, in Section VI the general conclusions and recommenda-
tions of this research effort are presented.

II. BACKGROUND STUDIES OF THE EROSION OF STEEL VENTS

Several investigations have been made of the erosion of
steel alloys in vented-combustor apparatus. Greaves, et al[1] and
Wiegand[2] both found that, above a critical pressure of the gases
in the combustor, erosion is due to melting of the steel speci-
mens. The melting region was identified as the linear portion
of the mass eroded versus propellant charge (or combustor peak
pressure) graph. Below this characteristic threshold pressure
for melting, the mass eroded curve is non-linear; in this low
pressure region the erosion was attributed to chemical effects.[2]
However, both of the above studies had sufficiently long test
times for the melting process to be established. Typical times
for the efflux of gases through the vent in Greaves, et al[1] exper-
iments were in the range of 0.5 - 1 sec. In comparison, typical
test durations in the present experiments range from 2 - 4 msec.
These short durations may not provide sufficient time for pre-
heating and melting of the steel alloys, thus allowing the chem-
ical interaction between the propellant gases and the steel
surface to govern the erosion process.

Greaves, et al[1] have shown (as did Vieille[3]) that the erodi-
bility of materials can be correlated with their melting tempera-
ture. This, however, must be considered with caution because it
assumes that erosion is due to melt-and-wipe-off. Tests per-
formed[4,5] on aluminum and titanium alloys have shown strong
augmentations of erosion rates resulting from chemical interactions
with the propellant gases. Furthermore, although the melting
temperature of titanium is greater than, say, the solidus tempera-
ture of carbon steel AISI 1020, titanium exhibits much larger
erodibility.

The linear behavior of the erosion curve (mass eroded vs mass
of charge) in the melting region was predicted by Nordheim, et al[6]
using a simplified steady-state melting theory. By adjusting the
Fanning friction factor (the Reynolds Analogy was invoked in their
analysis) they were able to correlate the experimental erosion
results of Greaves, et al.[2] A basic assumption in their close-form

solution was that the propellant burning time (pressurization process) was negligible compared to the exhaust time of the gases through the orifice. This solution is valid for prolonged test times. In the case of Loeffler, et al[7] experiments (23.5 cc combustor), a numerical approach was necessary. The non-steady melt-and-wipe-off theory of erosion has been applied to the erosion of aluminum alloys by Plett, et al.[5]

A comprehensive study of the chemical erosion of steel was made by Evans and co-workers,[8,9,10] who studied the erosive effect of high pressure and high temperature CO_2/CO mixtures. Following the work of Wiegand[2] and Greaves, et al,[1] they, too, observed the two-part nature of the erosion curve (in this case weight loss versus flame temperature of the mixture). They considered, how-ever, that separation of the two mechanisms is generally impossible because both mechanisms are strongly influenced by the temperature of the system. Their results showed that erosion increases with an increase of the flame temperature and with a decrease in the CO/CO_2 ratio. However, at CO/CO_2 ratios typical of a propellant composition ($CO/CO_2 > 1$), variation of the CO/CO_2 ratio has been shown[10] not to affect erosion.

Operating in the chemical region, Evans, et al,[8] found that trace concentrations of gaseous additives (SO_2, H_2S, NH_3, H_2) increase considerably the erosion of steel vents. Noting the catalytic effect of these additives on the formation of iron carbonyl, they concluded that the erosive action of CO/CO_2 mixture may be represented by the reaction

$$Fe + 5CO \rightarrow Fe(CO)_5$$

Tests[10] to isolate and identify iron carbonyl as the erosion product of the action of CO/CO_2 mixtures on steel vents were not very successful. However, this mechanism cannot be ruled out, due to the possible rapid decomposition of the iron carbonyl after its formation that makes it difficult to detect.

The general conclusion deduced by the above investigations of erosion of steel alloy vents by propellant gases is that erosion is controlled by two mechanisms, the melt-and-wipe-off

process and the chemical interaction of the steel surface with
the propellant gas. The controlling mechanism of erosion depends
on the experimental conditions. At relatively low peak pressures
or short duration experiments, the surface temperature of the
alloys does not reach the solidus temperature of the material
and erosion is controlled by the gas/solid reactions; on the
other hand, for relatively high combustor peak pressures or
long duration experiments, the steel surface melts and erosion
is controlled by the melt-and-wipe-off mechanism.

III. EROSIVE EFFECTS OF HIGH PRESSURE COMBUSTION GASES ON STEEL ALLOYS

Introduction to Vented-Combustor Erosion Studies

Vented-combustor studies of the erosive action of high pressure and high temperature propellant gases on steel alloy vents have been used widely as a means of studying the erosion of gun barrels. This approach provides an economical technique of studying the erosion characteristics of various steel alloys and of other high temperature materials. Furthermore, it isolates the thermochemical interactions of the propellant gases with the steel surface from the mechanical interaction of the projectile with the bore surface. Both of the above types of interaction contribute to the erosion of gun barrels. The thermo-chemical interactions result in erosion due to melting, cracking, and the chemical attack of the reactive species of the propellant gases on the bore surface. On the other hand, the mechanical interactions of the projectile with the bore surface produce wear of the barrel surface by abrasion and swagging.

The purpose of this study was to examine the erosion charac-teristics of steel alloys in short duration (2 - 4 msec) combustor experiments and to provide comparative erosion data for three types of steel alloys.

Apparatus and Materials

The vented-combustor erosion experiments were carried out by igniting and burning propellant in a small combustor (5 cc) and allowing the products of combustion to pass through a test orifice made of the material under examination. The vented-combustor shown schematically in Fig. 1 is the same as that used in Refs. 4 and 5. The rapid burning of the propellant powder in the combustor generates a supply of hot, high pressure propellant gas. The gas flows out the combustor through the vent orifice and the test orifice. For a given propellant loading, the pressure-time curve is controlled by the outflow through the vent orifice whose initial area is about 20 times the area of the test orifice.

Thus, the increase of the diameter of the test orifice due to erosion produces secondary effects on the pressure history of the combustor.

The pressure history of the combustor chamber was monitored by an ultra-high frequency Kistler 607 pressure transducer. The pressure and temperature transients of a typical test are shown in Fig. 2. The peak temperature in the combustor corresponds approximately to the isochoric flame temperature of the propellant.

For a given test firing, the erosion of the test specimen was obtained by the difference in mass of the specimen before and after the test. The mass reduction provides a gross measure of the erosion experienced by the specimen. For a more detailed examination of the effect of erosion on the steel orifices, microscopic examinations of the upstream and downstream side of the orifice and of sectioned orifices were performed.

The test specimen consisted of 0.250 cm thick steel alloy disk with a pre-drilled orifice at its center. The orifice diameter, in all the experiments reported, was 0.066 cm. The erosion tests were performed on three steel alloys, AISI 304 stainless steel, AISI 1020 carbon steel, and AISI 4340 chromium-molybdenum steel. Typical nominal compositions and room temperature properties of the above steels are shown in Tables 1 and 2 respectively.

Most of the experiments were carried out using IMR 4198 single-base propellant. However, for comparative purposes, a number of tests were performed using M1 single-base propellant and WC 846 deterred double-base propellant. The chemical composition and propellant gas properties of the three propellants used are shown in Table 3.

Results and Discussion

The erosion of the three test steel alloys as a function of the peak pressure of the combustor is shown in Fig. 3. In all three cases, erosion increases as the peak pressure increases. The peak pressure in the combustor provides a measure of the heat transfer at the gas/solid interface by means of the dependence of

the Reynolds number on density. The peak temperature in the combustor is approximately equal to the isochoric flame temperature of the propellant. Thus the higher the peak pressure, the higher the surface heat flux which results in higher surface temperature of the test material. Furthermore, the pressure is also a measure of the collision frequency of the gaseous molecules. The higher the pressure, the greater the number of collisions of the gaseous species with the solid surface. Both the surface temperature and the frequency of collisions of the gaseous species with the surface, augment the chemical interaction of the propellant gas with the steel surface.

Of the three alloy steels tested (in the vented chamber), the carbon steel AISI 1020 eroded the least, followed by the chromium molybdenum steel AISI 4340 and, last, the stainless steel alloy AISI 304. The differences in the erosion characteristics of the three alloys are more pronounced as the peak pressure increases. In the range of peak pressures lower than 2 kbar the erosion of the three alloys is indistinguishable as a result of the scattering of the experimental data.

The difference of the erosion characteristics of the three alloys are due to their varying thermal properties. Figures 4 and 5 show the variation of thermal conductivity and specific heat between pure iron and the alloy steels used in the experiments as a function of temperature. In Fig. 5, because of the unusual shape of the specific heat of α-iron curve [peak of the specific heat occur due to allotropy change, i.e., α-iron (body-centered cubic lattice) becomes γ-iron (face-centered cubic lattice)], and because specific heat data for AISI 1020 and AISI 4340 as a function of temperature is not available, the specific heat curve of a carbon steel of known composition was plotted. This curve shows that sharp changes in the specific heat of steel alloys occur when undergoing a change of phase. Furthermore, Fig. 5 shows that at high temperatures (> 1300 K) the differences in the thermal properties of these alloys diminish. It is obvious, however, from a comparison of the

thermal properties of the three alloys, especially the thermal
conductivity curves, that the stainless steel alloy AISI 304
has lower thermal properties than the other two alloys. Low
values of thermal conductivity and specific heat result in high
values of the surface temperature of the specimen. This results
in higher erosion rates. Furthermore, by considering the room
temperature thermal conductivity of AISI 1020 and AISI 4340,
it is expected that AISI 4340 will erode more than AISI 1020.
This is indicated in the present experiments (see Fig. 3).

The variation of the erosion characteristics of the three
alloys with respect to peak pressure provides also a clue to
the nature of the erosion process. As we have stated earlier,
there are two leading hypotheses on the mechanism of erosion of
steel alloys: (1) the melt-and-wipe-off mechanism, based on the
premise that erosion occurs due to inert heating and melting
of the surface of the test specimen, with subsequent removal of
the melt by the aerodynamic forces of the flow, and (2) the
chemical mechanism, based on the premise that erosion is due
to the chemical interaction between the propellant gases and the
solid surface.

The steady-state one-dimensional melting rate is given by

$$\dot{m} = \frac{q_W}{[\Delta H_m + c(T_m - T_0)]} \tag{1}$$

The properties of the alloys in Eq. (1) are evaluated at the
solidus temperature of the alloys. Since at these high tempera-
tures the properties of the tested alloys do not differ appreciably
and likewise their solidus temperature, one will expect that
their melting rate should be approximately the same. On the
other hand, the preheating time, i.e., the time required for the
surface temperature of the specimen to reach its solidus tempera-
ture, which is given by Eq. (2) will vary considerably owing to
the large differences of their thermal properties.

$$t_{pr} = \frac{\pi}{4}(\rho c K)(T_m - T_0)^2/q_W \tag{2}$$

Equation (2) is valid for one-dimensional geometry, constant heat
flux system. Thus it is assumed, if the inert mechanism of
erosion is the controlling mechanism, that the erosion character-
istics of the three alloys will differ appreciably at the lower
peak pressure range (onset of erosion).

On the other hand, if we assume that the chemical inter-
action between the gaseous propellant combustion products and
the steel alloy is the governing mechanism of erosion, then the
erosion characteristics of the three alloys are in accordance
with this hypothesis. The rate of chemical reaction is dependent
on the surface temperature through the Arrhenius expression
$\exp(-E/RT_s)$, which indicates that as the temperature increases,
the reaction rate and hence the erosion will increase exponential-
ly. Furthermore, for a given surface temperature difference
between two alloys, the difference in their reaction rates will
increase as the level of temperature increases. Therefore the
experimental erosion results of the three steel alloys indicate
that at least the onset of erosion is very dependent on the
chemical reactions between the gaseous species and the solid
surface.

Figures 6 and 7 show the erosion of the three steel alloys
tested as a function of the number of firings. Figure 6 is a
sequence of 5 firings and Fig. 7 is a sequence of 20 firings.
These tests were performed at approximately constant combustor
conditions. Similar to the results of Fig. 3 the erosion experi-
enced by the stainless steel alloy AISI 304 is greater than by
AISI 4340 and AISI 1020. The linear behavior of the eroded
mass versus number of firings curve indicates that the erosion
process of these alloys, under the particular environmental
conditions are apparently independent from test to test, i.e.,
the erosion experienced by a test specimen produces minor physical
and chemical alterations on the eroded surface that apparently
do not affect the subsequent erodibility of the material. The
linearity of the erosion results with respect to number of firings
excludes the possibility of accumulation of oxide on the eroded

surface; however, it does not exclude the possibility of oxide formations that were removed by the shear forces of the flow and similarly, integranular changes are not excluded.

Figure 7 (sequence of 20 firings) shows a non-linear relationship between the mass loss and number of firings in the case of AISI 304. The decrease of erosion experienced by the stainless steel alloy at high number of firings results from loss of combustor pressure because of the large erosion experienced by the alloy. The loss of pressure between test No. 1 and test No. 20 was 0.7 Kbars.

The erodibility of the three tested alloys, expressed as average mass eroded per firing, is shown on Table 4 along with values of the parameter $(\rho c K)^{-1/2}$ which represents a measure of the surface temperature of the alloy reached during the test cycle. The higher the value of $(\rho c K)^{-1/2}$, the higher the value of the surface temperature of the alloy. The order of erodibility of the three alloys as determined by the experimental results is shown to coincide with the order obtained by the use of the parameter $(\rho c K)^{-1/2}$. The relative magnitudes of erosion, however, are not predicted. The experimental results, for example, indicate that alloy AISI 304 erodes approximately five times more than alloy AISI 1020, whereas evaluation of the above parameter predicts the number to be 2.5. This discrepancy may be due to the use of room-temperature thermal properties of the alloys.

The effect of curvature on the erosion characteristics of AISI 1020 carbon steel is shown in Fig. 8. This is a plot of mass eroded per unit surface area versus number of firings for two cases: (1) cylindrical orifice, and (2) rectangular flow passage. The height of the rectangular passage is 0.013 cm, compared to 0.277 cm for its width, which provides two flat surfaces for the chemical and thermal interaction with the propellant gases. In order to have similar pressure and temperature histories of the propellant gases in the combustor, the cross-sectional area of the two configurations are approximately the same. As shown in Fig. 8 the erosion per unit surface area

experienced by the flat surfaces is greater than the erosion experienced by the circular orifice. The difference in the erosion of the two geometries is due to the effect of curvature on the heat dissipation in the interior of the specimen; the smaller the curvature, the smaller the portion of heat dissipated in the interior of the test disk. In the limit of zero curvature, i.e., one-dimensional slab, the heat dissipated in the interior is minimum, with the result of maximum surface temperature, hence, maximum erosion rate.

A comparison of the erosive action of three nitrocellulose-based propellants, IMR 4198, Ml, and WC 846 on the three test steel alloys is shown on Table 5. These tests were performed with no vent because of the difficulty in igniting the WC 846 propellant. In all three cases, the erodibility of the steel alloys have the same order, i.e., AISI 304 followed by AISI 4340, followed by AISI 1020. For a constant peak pressure, propellant Ml (T_v = 2530 K, $\Sigma(H_2O + CO_2)$ = 0.196) produces less erosion than the IMR 4198 propellant (T_v = 3000 K $\Sigma(H_2O + CO_2)$ = 0.319). This is consistant with earlier studies[9,11] that showed that the erosive action of propellants on steel vents can be correlated with their isochoric flame temperature, i.e., the greater the flame temperature of the propellant, the higher its erosive action. However, in the case of oxidative attack on the steel surface by the gaseous species, the concentration of the oxidizing species of the propellant gases CO_2 and H_2O may play an important role in the magnitude of erosion. This has been verified in the case of erosion of aluminum alloys by the action of high pressure, hot propellant gases.[4] To isolate the effects of temperature, and oxidizing species concentration, WC 846 double-base propellant was tested. WC 846 has the same concentration of CO_2 and H_2O species but lower flame temperature (T_v = 2834). A comparison of IMR 4198 and WC 846 showed that WC 846 produces more erosion than IMR 4198. However, this comparison is not completely valid because of the difference in the pressure cycles of the two propellants. The WC 846 propellant granules are deterred so

that the outer layer of propellant has a lower burning rate and
lower flame temperature. The difference in the burning rate of
the two propellants produces variation of the pressure cycle
with the consequential variation in the heating cycle of the test
alloy. Figure 9 shows a comparison between the pressure-time
traces of IMR 4198 and WC 846 propellants. Due to the slower
burning rate of WC 846, the effective test time is longer in
comparison to the test time of the IMR 4198 propellant, which may
result in greater erosion. Thus, for a proper comparison of the
erosive action of propellants, the burning rate of these propellants
must be similar. This condition was not met in the comparison
between M1 and IMR 4198 propellants. However, a qualitative
comparison was made because although the M1 propellant had a
greater test time than that of the IMR 4198, the erosion produced
by the M1 propellant was less than that of the IMR 4198 propellant.

The erosive action of sulphur on steel alloy #4340 was
investigated in a special test series. One percent by weight
of sulphur powder was mixed with the IMR 4198 propellant. This
addition provided no alterations in the pressure history of the
combustor. Attempts, however, to use a higher percentage of
sulphur were not successful because the presence of sulphur
altered considerably the pressure history of the combustor. In
general, the addition of sulphur tended to increase the pressuriza-
tion time of the propellant.

The erosion results of the above tests, shown in Table 6,
indicate that the addition of 1% sulphur produces different
effects depending on the peak pressure of the combustor. At
low peak pressures (2 kbar or lower) sulphur increases erosion,
whereas at high peak pressures (2.75 kbar or higher) erosion is
decreased by the addition of 1% sulphur. The increase of erosion
at 2.0 kbar was by a factor of 1.6 times, whereas at 2.75 kbar
erosion was decreased by a factor of 1.1. Similar results were
obtained by Wiegand[2] who made comparative studies of the erosion
of cold rolled AISI 1020, using primers with and without sulphur.
The increase in erosion of steel alloys by the addition of sulphur

at low peak pressures was attributed to the fact that in this region the chemical action of the propellant gases is the controlling mechanism of erosion and that sulphur increases the reactivity of the propellant gases.

The role of sulphur in the chemical attack of the steel alloys by the propellant gases is not well understood. The leading hypothesis[8,9] is that hydrogen sulphide (H_2S), produced by the reaction of sulphur with propellant gases, acts as a catalyst for the carbonyl reaction

$$Fe + CO \rightarrow Fe(CO)_5$$

which is considered to represent the chemical interaction of the propellant gases and the steel surface. Another hypothesis,[12] however, is that H_2S attacks iron to form ferrous sulphide

$$Fe + H_2S \rightarrow FeS + H_2$$

Augmentation in erosion may result due to either: (a) the formation of FeS and the removal of FeS by the shearing forces of the flow, or (b) the above reaction, believed to be highly exothermic, may provide enough heat to increase considerably the surface temperature of the alloy which in turn will increase the reaction rate of the steel surface.

The effect of sulphur at high peak pressures is very unclear. No explanation has been given in the literature. One possible explanation of the observed reduction in erosion is that at high peak pressures the surface temperature of the specimen reaches the melting or decomposition temperature of the ferrous sulphide. Both processes are endothermic which will result in a net decrease of the surface heat flux and a corresponding decrease in the erosion.

IV. EROSIVE EFFECTS OF VARIOUS PURE GASES ON STEEL ALLOYS

Introduction to Ballistic Compressor Erosion Studies

Studies of the chemical attack of high pressure and temperature propellant gas on steel specimens are greatly complicated by the large number of reactive gases present in a propellant gas which makes the identification of the chemical interactions occurring during the erosion process practically an impossible task. The adiabatic compression of pure gases to high temperature and pressure conditions (similar to combustor conditions) provides a means of studying the erosive effect of an individual gas on steel alloys. The ballistic compressor performs such a task by allowing a low pressure ($\sim$ 300 psi) driver gas to drive an inertial piston to compress adiabatically the desired test gas. The compressed high temperature test gas is allowed to interact with the steel surface by flowing through the test orifice. The ballistic compressor is an ideal tool for erosion studies because it isolates the erosive action of the individual gases that constitute the propellant gas. Furthermore, it provides a means of differentiating between chemical and pure thermal effects by using an inert gas.

The purpose of this investigation was to study the erosive action of pure gases such as N_2, H_2, CO, CO_2, O_2 and H_2O on three steel alloys, AISI 304 stainless steel, AISI 1020 carbon steel and AISI 4340 chrome-moly steel.

Apparatus

A ballistic compressor utilizes a reservoir of driver gas to drive an inertial piston to compress adiabatically the desired test gas. A schematic diagram of the ballistic compressor used in the erosion tests is shown in Fig. 10. It consists mainly of a reservoir where the driver gas is stored, a compression chamber where the test gas is initially situated, an inertial piston, and the test section which serves as a holder for the test specimen and as an exhaust port for the test gas flowing through the test orifice.

The driver gas in the reservoir is allowed to flow through the transition section to the compression chamber by means of an actuating valve. Initially, the actuating chamber is pressurized above the pressure of the driver gas in the reservoir, so that the actuating piston shuts the passage to the compression chamber. By discharging the gas in the actuating chamber, the pressure differential thus produced drives the actuating piston to the right (see the diagram), thus opening the transition passage. The driver gas that flows through the transition section drives the inertial piston which adiabatically compresses the test gas occupying the compression chamber volume to the left of the ballistic piston. The test metal disk is pre-drilled to the desired size (0.066 cm diameter) and placed in the interior of the test section in close contact with the test gas. The compressed high-temperature test gas flows through the test orifice to the surrounding atmosphere.

A photograph of the ballistic compressor apparatus is shown on Fig. 11. Major dimensions of interest are:

Reservoir Volume   = $0.0137 \ m^3$

Diameter of Compression Chamber   = 3.871 cm

Length of Compression Chamber   = 152.4 cm

Length of Inertial Piston   = 15.2 cm

Mass of the Piston   = 1.34 Kg

The pressure history of the test gas was monitored by an ultra-high frequency Kistler 607 piezoelectric pressure transducer. Typical pressure traces are shown in Fig. 12.

Results and Discussion

Figure 13 shows a comparison of the erosion characteristics of chrome-moly steel AISI 4340 obtained in a multi-firing sequence test using (a) the vented-combustor (IMR 4198 propellant, T_v = 3000 K) and (b) the ballistic compressor (test gas: Air; T_{max}(ideal) = 3000 K). Both the vented combustor and ballistic compressor tests show a linear relation between the mass erosion experienced by the test specimen and the number of firings, which

indicates that any physical and chemical alterations undergone
by the eroded surface do not affect the erosion process. Further-
more, since it has been established that the erosion of the steel
alloy by the action of high pressure and temperature air is due
to the oxidative attack of oxygen (a conclusion developed in the
remainder of this section) it can be concluded that the shear
forces of the flow remove the oxide scale. The existance of an
oxide scale on the eroded surface would have provided a partial
protection to chemical attack which would have been indicated by
a reduction of erosion with the number of firings. At present
no comparison can be made between the erosion results obtained
using the two apparatus because the pressure cycles and, more
important, the temperature cycles of the two erosion apparatus are
distinctly different.

The erosion of AISI 4340 steel as a function of the peak
pressure of the test gas (air) is shown in Fig. 14. Erosion is
shown to increase very sharply with the peak pressure. This
results because, unlike the vented combustor tests that have for
any peak pressure approximately the same peak temperature
(isochoric flame temperature of the combustor), in the ballistic
compressor the work done by the driver gas is used to raise the
temperature of the test gas, i.e., the pressure and temperature
rise together. If the heat flux at the gas/solid interface is
expressed by the usual relation

$$q_s = h(T_g - T_W)$$

then an increase in temperature increases the surface heat flux
through the temperature differential $(T_g - T_W)$, whereas an
increase in pressure increases the surface heat flux through the
Reynolds number dependence of the convective coefficient h.

The erosive effects of various pure gases and gas mixtures
on the three test alloys, stainless steel AISI 304, carbon steel
1020 and chromium molybdenum steel AISI 4340, are shown in
Tables 7, 8 and 9. These results show no particular advantage of
one alloy over the other alloys with respect to their erodibility.
Three test gas mixtures show appreciable erosion with respect to
the erosion obtained using nitrogen gas. These test gases are

air, O_2/N_2 mixture in ratio of 40/60 by mass and hydrogen. The erosive action of the first two gases is due to the oxidative attack of oxygen on the steel surfaces. On the other hand, the augmented erosive action of hydrogen in comparison to nitrogen may be due to the high diffusivity of hydrogen which increases the surface heat transfer. At room temperature, for example, the thermal conductivity of H_2 is 4.02×10^{-4} cal/cm-secK, whereas the thermal conductivity of N_2 is 5.77×10^{-5} cal/cm-secK; one order of magnitude difference. The possibility, however, that H_2 may chemically attack the iron or the alloying elements of steel cannot be ignored.

The augmentation of erosion of steel alloys due to surface chemical attack by oxygen is demonstrated in Fig. 15. This is a plot of mass eroded of AISI 4340 versus mole fraction of O_2 in O_2/N_2 mixture. This relation is linear indicating that the overall chemical reaction between oxygen and steel is a first order reaction, i.e., the rate of erosion can be written as

$$\dot{m} = A x_{O_2} e^{-E/RT}$$

This relation, however, is correct when the mole fraction of oxygen is greater than 0.08. When the mole fraction is less than 0.08 erosion is negligible.

The linear behavior of the mass eroded versus oxygen mole fraction curves indicates, moreover, that the controlling step of the oxygen/steel interaction is the chemical reaction between O_2 and steel at the surface.

V. METHODS OF MEASURING MASS REMOVAL OF STEEL ALLOYS

The purpose of this part of the investigation was to evaluate methods of measuring small mass removal of steel alloy vents due to the erosive action of high pressure and high temperature gases. The emphasis was in developing techniques by which surface re-gressions of the order of $1 - 20$ μm can be measured. The range considered includes the range of mass removal experienced in actual gun systems. Typical erosion results of a 105 mm gun system is shown in Table 10.[13]

The methods considered to measure the mass removal of steel alloys were:

    (1) Weight-loss measurements using ultra-high sensitive balance (accurate to 0.00001 gm).

    (2) Gas-flow through enlarged drilled orifices.

    (3) Surface loss measurement by nulcear reaction methods:

        (a) Diffused oxygen detection.

        (b) Removal of tagged constituents.

In the following section, we will discuss each method, pointing out the advantages and disadvantages.

Weight-loss Measurements using Ultra-High Sensitivity Balances

At present, the mass loss due to erosion is determined using a Mettler Model H20 analytical balance. Its accuracy is $\pm$ 0.01 mg. Assuming that erosion occurs uniformly along the orifice, and using typical dimensions of the test orifice we obtain that the change of the mean orifice radius due to erosion is 24 μm/mg of erosion of steel alloy. Thus, with the precision of our analytical balance a removal of mass of less than 1 μm from the test surface can be obtained. More accurate analytical balances are commercially available such as the Mettler Model M5 with a weighing range of $0 - 20$ g and an accuracy of $\pm$ 0.001 mg. Better accuracy, however, will not be useful because we are probably at the limit of practicality in weighing techniques since effects such as small amounts of metal removed during specimen mounting and demounting and contamination already influence the measurements.

In addition to the above influences on weight measurements, another disadvantage of the weighing techniques is that they do not give any information on the spatial distribution of erosion. Microscopic observations have shown that erosion experienced by a test specimen is generally concentrated in the upstream section where the surface heat transfer is greater. A further limitation of these techniques is that accuracy decreases drastically as the weight of the specimen increases.

Gas-Flow through Enlarged Drilled Holes

This technique utilizes the rate of filling of an evacuated container exposed to a constant temperature and pressure environment. The test specimen serves as the inlet port to the container. An exact determination of the size of the orifice requires the experimental measurement of the flow rate through the orifice coupled with a theoretical prediction of the flow rate in terms of the orifice size and other physical parameters of the system. The theoretical analysis provides the first disadvantage of this method because, due to the irregular size of the orifice, the discharge coefficient that accounts for the real effects of fluids will be variable and difficult to estimate. Another disadvantage is that the measured orifice size will represent an average value. Furthermore, the possibility exists that even though the specimen eroded, its final dimensions may be smaller due to thermal expansion and intergranular changes.

Surface Loss Measurements by Nuclear Methods

Under the heading of nuclear methods are two candidate techniques; (1) diffuse oxygen detection and (2) removal of tagged constituents of steel. The former technique was developed by Nieler at BRL, and consists of measuring the pre-implanted oxygen concentration in the surface layer of the steel alloy before and after erosion. The detection of the oxygen distribution in the solid layer is obtained by measuring the α-particle emission characteristics due to the reaction $^{16}O(d,\alpha)^{14}N$. By relating the difference in α-radiation resulting from the test to the

depth distribution of oxygen, we can obtain a measure of the surface removed. The disadvantages of this method are (a) the depth distribution of oxygen must be known accurately, (b) difficulties in pre-implanting oxygen in steel alloys, and (c) the depth distribution may vary during erosion due to back diffusion of oxygen. The seriousness of these disadvantages have not been fully evaluated nor do we know to what extent proper care can overcome experimental difficulties.

The second method, proposed both by Niiler and Princeton University, consists of measuring the removal of a tagged constituent of the steel alloy. The tagged element can be the radioactive cobalt generated by the reaction $^{56}Fe(p,n)^{56}Co$. The ^{56}Co is a γ-emitter (1.2 Mev, 0.8 Mev) with a half-life of 77 days. Measurement of the γ-emission of the steel alloy before and after an erosion test, assuming a known distribution of ^{56}Co, will allow determination of the mass removal due to erosion. The main disadvantage of this method, as in the case of diffused oxygen detection, is that auxiliary measurements must be made to obtain the depth-distribution of ^{56}Co. However, for a given proton beam exposure condition, once the distribution is known, the measurement of mass removal can be done routinely using in-house γ detectors without any radiation-hazard protection.

The practicability of both the above nuclear methods has been successfully demonstrated by Niiler. Table 11 shows the results of a preliminary test performed by Niiler to determine mass removal by the radioactive method.

The accuracy of the technique will depend upon the accuracy of the depth-distribution measurement of ^{56}Co and upon the accuracy of the detectors. Niiler has indicated that the accuracy of these measurements should be expected to be $\pm$ 1 μm.

VI CONCLUSIONS

Erosion of Steel Alloys by Propellant Gases

The experimental investigation of the erosion of steel alloys by propellant gases, using the vented-combustor apparatus, provided the following conclusions:

1. In short duration combustor tests (2-4 msec) the erosion of steel alloys is strongly controlled by the chemical interaction of the propellant gases with the steel alloys.

2. The erosion experienced by the steel alloys is dependent upon the thermal properties of the alloys. The parameter $(\rho ck)^{1/2}$ was found to qualitatively predict the relative erosivity of these alloys. This parameter is a measure of the surface temperature attained by the alloys for a given heat flux rate and a given test duration.

3. Erosion is strongly influenced by the geometry of the test orifice. The smaller the curvature of the test wall the smaller the portion of heat dissipated in the interior of the test specimen and the greater the erosion. Flat surfaces experience the greatest erosion.

4. The erosion of the three alloys tested was found to be linearly dependent on the number of firings, which indicates that any physical or chemical alterations produced by the erosion process do not influence the future erosivity of these alloys. The average mass removal per firing of AISI 304 stainless steel, AISI 1020 carbon steel, and AISI 4340 chrome-moly steel were 1.78 mg, 0.34 mg and 0.45 mg, respectively.

5. The addition of 1% sulphur in IMR 4198 propellant was found to have different effects on erosion, depending on the level of peak pressure. At high peak pressures (> 2.7 Kbar) the addition of sulphur decreases erosion, whereas at low peak pressures it increases erosion. The increase of erosion at low pressures was attributed to the chemical interaction of sulphur with the propellant gas/steel alloy system. At high

peak pressures the role of sulphur on the erosion of steel alloys is very unclear.

Erosion of Steel Alloys by Pure Gases

The erosion of steel alloys under the action of high temperature and high pressure pure gases was studied utilizing the ballistic compressor. The test gases used were N_2, H_2, CO, and CO_2/A, N_2/O_2 and $N_2/H_2/O_2$ mixtures.

With the exception of the oxygen containing gases (air, O_2/N_2 mixtures) and hydrogen, the mass removal experienced by the steel alloys under the action of N_2, CO, CO_2/A and $N_2/H_2/O_2$ mixtures was very small (on the order of 0.25 mg or less). The small mass removal rate obtained by the erosive action of the above test gases is due to the relatively short test cycle of the ballistic compressor (< 1 msec) coupled with a probable insufficient shearing force of the flow to remove the chemically altered layer from the surface of the test orifice. Thus, the test gases may chemically attack the test surface, but with the present method of measuring erosion (i.e., weighing the sample before and after a test), we are not able to determine the magnitude of gas/solid interaction. Therefore, more discriminating methods of evaluating the erosive attack of pure gases on steel alloys should be pursued.

Most significantly, the erosion results of the three test alloys do not show distinct differences; that is, the three alloys (which are strikingly different in composition) under the action of a given test gas erode nearly the same amount. In view of the vented combustor results that showed that the three steel alloys tested have distinct erosion characteristics, the above result would have been difficult to predict. An explanation of this important result is being studied as part of the follow-on studies. The erosivity of H_2 in comparison to N_2 is attributed to the high diffusivity of H_2 that greatly augments the surface heat transfer. However, the possibility of

H_2 chemically attacking the iron or the alloying elements of steel cannot be ignored. The erosive action of air and N_2/O_2 mixtures is due to the chemical interaction of oxygen with the steel surface.

The erosion of the chrome-moly steel alloy AISI 4340 was found to increase linearly with the mole fraction of O_2 in O_2/N_2 mixtures. The experimental results were very consistant and no appreciable deviations of the erosion of the test specimen under the action of a particular O_2/N_2 mixture were observed. The consistancy of these results provide further evidence of the potential of the ballistic compressor as a tool for studying high pressure and temperature gas/solid interactions. Erosion was negligible when the mole fraction of O_2 was less than 0.08. The linear dependence of erosion on the oxygen mole fraction indicates that the rate-determining step in the oxidation scheme of steel alloy is the surface reaction of oxygen with iron.

The evaluation of methods to measure small mass removals of steel alloys by the action of erosive gases showed that the two nuclear methods considered have very attractive potentials. Both the diffused oxygen detection and radioactive constituent removal detection, not only can measure small surface removals, but can be used to obtain a rough mapping of the eroded surface.

The general recommendation of this study is that investigation of the erosion processes by gravimetric methods alone are insufficient to provide fundamental information on the erosive action of high pressure and high temperature gases on steel surfaces. Future research should be directed toward the development of diagnostic tests such as chemical and metallurigcal investigation of the eroded surface and spectroscopic studies of the gaseous jet. Gravimetric methods are useful in obtaining the overall effect of erosion, however, they provide little information on the nature of erosion.

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Table 1

Nominal composition of the steel alloys used in the erosion tests

	STEEL ALLOYS, AISI #		
NOMIMAL COMPOSITION	304	1020	4340
C	0.08 (max)	0.18-0.23	0.38-0.43
Mn	2.00 (max	0.30-0.60	0.60-0.80
Si	1.00 (max)	0.10	0.20-0.35
Ni	8-12		1.65-2.00
Cr	18-20		0.70-0.90
Mo			0.20-0.30
P (max)		0.040	0.040
S (max)		0.050	0.040

Table 2

Thermal Properties of Pure Iron
and of the Three Steel Alloys Under Investigation

METAL OR ALLOY	DENSITY ρ g/cm^3	THERMAL * CONDUCTIVITY K cal/cm s °K	HEAT * CAPACITY c cal/g°K	LATENT HEAT OF MELTING ΔH_L cal/g	SOLIDUS TEMPERATURE T_M °K
Iron (pure)	7.87	0.192	0.108	65.0	1810
AISI #304	8.02	0.041	0.12	~65.0	1700
AISI #1020	7.86	0.124	0.107	~65.0	1789
AISI #4340	7.86	0.090	~0.107	~65.0	1778

*At room temperature.

Table 3

Propellant Compositions and
Combustion Gas Properties

PROPELLANT	COMPOSITION	PRODUCT COMPOSITION MOLE FRACTION	PROPERTIES
IMR 4198	90.5 NITROCELLULOSE (13.15% N) 6.0 DINITROTOLUENE 0.7 DIPHENYLAMINE 0.3 GRAPHITE 0.5 POTASSIUM SULPHATE 2.0 MOISTURE	$CO = 0.439$ $CO_2 = 0.104$ $H_2 = 0.126$ $H_2O = 0.215$ $N_2 = 0.111$ $*F.R = 0.005$ $^{†}X_{ox} = 0.319$	$T_V = 3000.\ °K$ $M = 24.25$ $F = 344.041\ FT-LBF/LBM$ $a = 1122.9\ M/S$ $\gamma = 1.226$
WC 846	80.0 NITROCELLULOSE (13.15% N) 10.0 NITROGLYCERIN 5.0 DIBUTYLPHALATE 1.0 DIPHENYLAMINE 0.4 GRAPHITE 1.6 MOISTURE	$CO = 0.428$ $CO_2 = 0.095$ $H_2 = 0.147$ $H_2O = 0.224$ $N_2 = 0.104$ $F.R = 0.002$ $X_{ox} = 0.319$	$T_V = 2834.\ °K$ $M = 23.44$ $F = 336.235\ FT-LBF/LBM$ $a = 1111.9\ M/S$ $\gamma = 1.230$
M-1	82.75 NITROCELLULOSE (13.15% N) 10.0 DINTROTOLUENE 5.0 DIBUTYLPHALATE 1.0 DIPHENYLAMINE 1.25 MOISTURE	$CO = 0.501$ $CO_2 = 0.056$ $H_2 = 0.201$ $H_2O = 0.140$ $N_2 = 0.099$ $F.R = 0.003$ $X_{ox} = 0.319$	$T_V = 2528.\ °K$ $M = 22.26$ $F = 315.829\ FT-LBF/LBM$ $a = 1087.4\ M/S$ $\gamma = 1.252$

* F. R = FREE RADICALS

† $X_{ox} = \Sigma(H_2O + CO_2)$ MOLE FRACTION

Table 4

Qualitative agreement of the
magnitude of surface temperature criterion
with experimental results of the three steel alloys

STEEL ALLOY AISI #	AVERAGE MASS ERODED PER FIRING mg	$*(k\rho c)^{-1/2}$ $cm^2 cal^{-1} K^{-1} s^{-1/2}$
304	1.78	5.0
4340	0.45	3.6
1020	0.34	3.1

*Properties evaluated at room temperature

Table 5

Comparison of the Erosive Action of IMR-4198
with M1 and WC846 Propellants

Propellant	Peak Pressure Kbar	ERODED MASS mg		
		Steel Alloy AISI #		
		304	1020	4340
IMR 4198	2.96	6.06	1.91	2.15
M1		2.96	1.58	1.66
IMR 4198	3.24	5.66	2.17	2.89
WC 846		7.32	3.36	3.40

Table 6

Effect of Sulphur Additive on the Erosion of Steel Alloys.
At Low Peak Pressures Sulphur Increases Erosion.
At High Peak Pressure it Decreases Erosion.

Propellant: IMR 4198
$T_V = 3000°K$
Erosion Disk = AISI #4340
Orifice Diameter = 0.066 cm
Orifice Thickness = 0.25 cm

Percent Sulphur	Peak Pressure Kbar	Total Mass Eroded From Five Consecutive Tests mg
0%		0.25
1	1.48	0.29
0%		0.34
1%	2.0	0.54
0%		1.88
1%	2.76	1.68
0%	3.77	4.31
1%	3.41	3.15

Table 7

Summary of the Ballistic
Compressor Tests of AISI 304

EROSION DISK: AISI #304

ORIFICE DIA. = 0.066 cm

DISK THICKNESS = 0.254 cm

Test Gas (Mass Fractions)	Peak Pressure Kbar	Mass Eroded* mg
N_2	3.48	0.01 ± 0.01
H_2	3.55	1.23 ± 0.22
CO	3.44	0.13 ± 0.05
CO_2/A (48/52)	3.68	0.04 ± 0.03
H_2O/N_2 (5/95)	2.9	0.00
AIR	3.34	1.31 ± 0.38
O_2/N_2 (40/60)	3.86	6.29 ± 0.56

* Average of 3 tests

Table 8

Summary of the Ballistic
Compressor Tests of AISI 1020

EROSION DISK: AISI #1020

ORIFICE DIA = 0.066 cm

DISK THICKNESS = 0.254 cm

Test Gas (Mass Fractions)	Peak Pressure Kbar	Mass Eroded* mg
N_2	3.41	0.23 ± 0.10
H_2	3.45	0.89 ± 0.13
CO	3.38	0.25 ± 0.05
CO_2/A (48/52)	3.59	0.14 ± 0.08
H_2O/N_2 (5/95	2.90	0.05 ± 0.02
AIR	3.34	1.25 ± 0.43
O_2/N_2 (40/60)	3.87	6.49 ± 0.36

* Average of 3 tests

Table 9

Summary of the Ballistic
Compressor Tests of AISI 4340

EROSION DISK: AISI #4340

ORIFICE DIA = 0.066 cm

DISK THICKNESS = 0.254 cm

Test Gas (Mass Fractions)	Peak Pressure Kbar	Mass Eroded* mg
N_2	3.20	0.28 ± 0.11
H_2	3.45	0.7 ± 0.02
CO	3.31	0.12 ± 0.04
CO_2/A (48/52)	3.55	0.01 ± 0.01
H_2O/N_2 (5/95)	2.80	0.22 ± 0.05
AIR	3.41	1.26 ± 0.13
O_2/N_2 (40/60)	3.74	6.76 ± 0.10

* Average of 3 tests

Table 10

Typical Erosion Results of a 105 mm Gun

Tube	Additive	Average Bore Wear Per Round (μm)
Unplated	None	18
Chrome-Plated	None	13
Unplated	Polyurethane	3

Gun - 105 mm - M68

Propellant - M30

Chamber Pressure - 3.8 Kbar

Table 11

Niiler's Experiment to Measure Mass Removal of Steel Vent by Nuclear Method

50°

6 Mev BEAM
FOR 1 HOUR

INCIDENT CHARGE
10^{-3} COULOMB

13 μm PENETRATION

$$_{26}Fe^{56} + {}_1p^1 \rightarrow {}_{27}Co^{56} + {}_0n^1$$

γ

TEST VENT   1.1"

5/8"
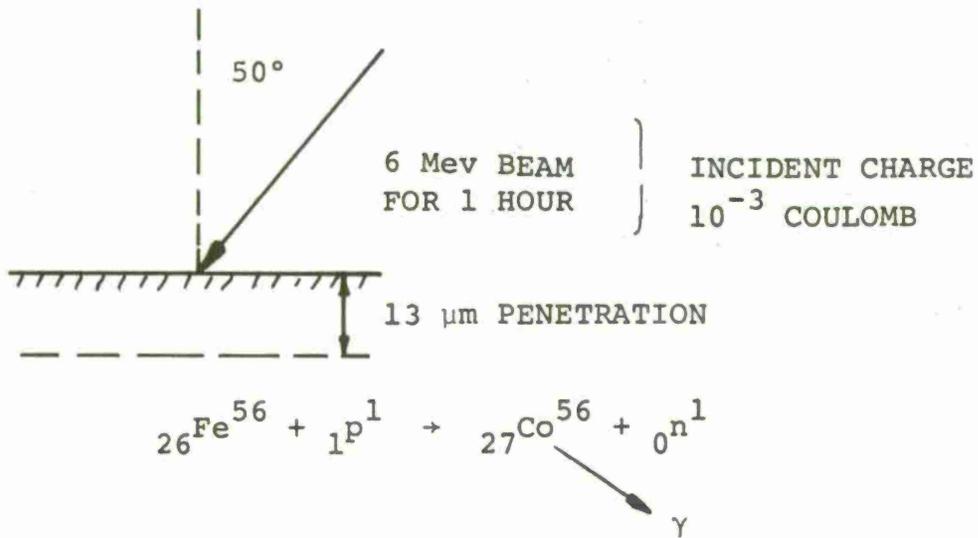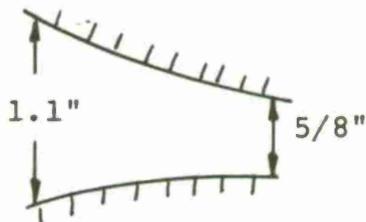
PROPELLANT: 85g M2

No. OF FIRINGS	γ-RADIATION COUNTS (15 MINUTE PERIOD)
0	16×10^3
1	9×10^3
3	300
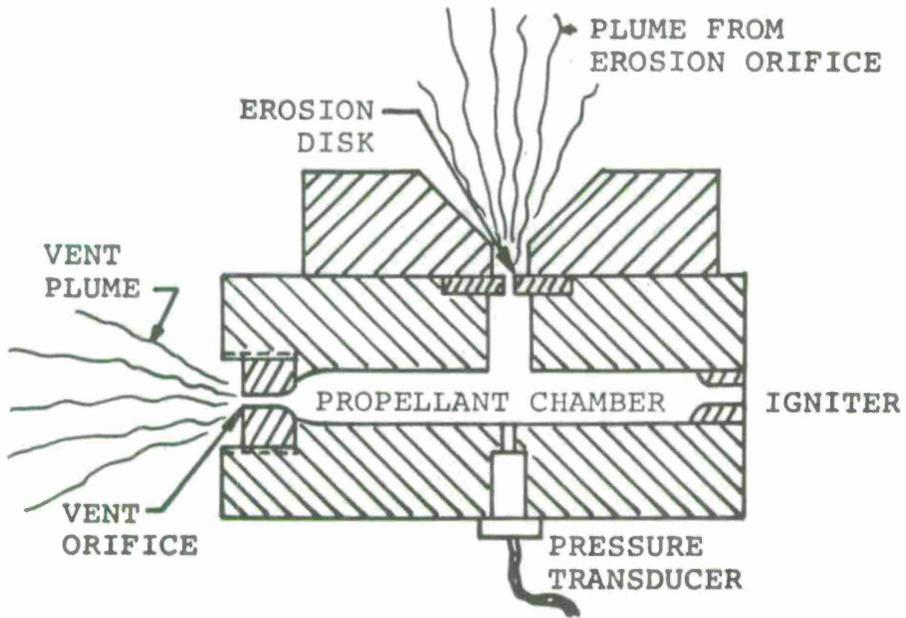
Fig. 1 Schematic diagram of the vented-combustor erosion apparatus.

PRESSURE
(68.95 MN/M^2/DIV)

TIME (0.5 MSEC/DIV)

PRESSURE
TEMPERATURE

TEMPERATURE
(COMPUTED)

PRESSURE
(MEASURED OR
COMPUTED)

TIME
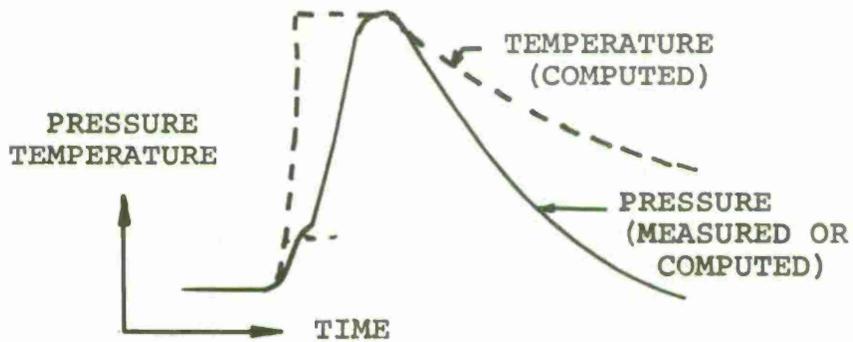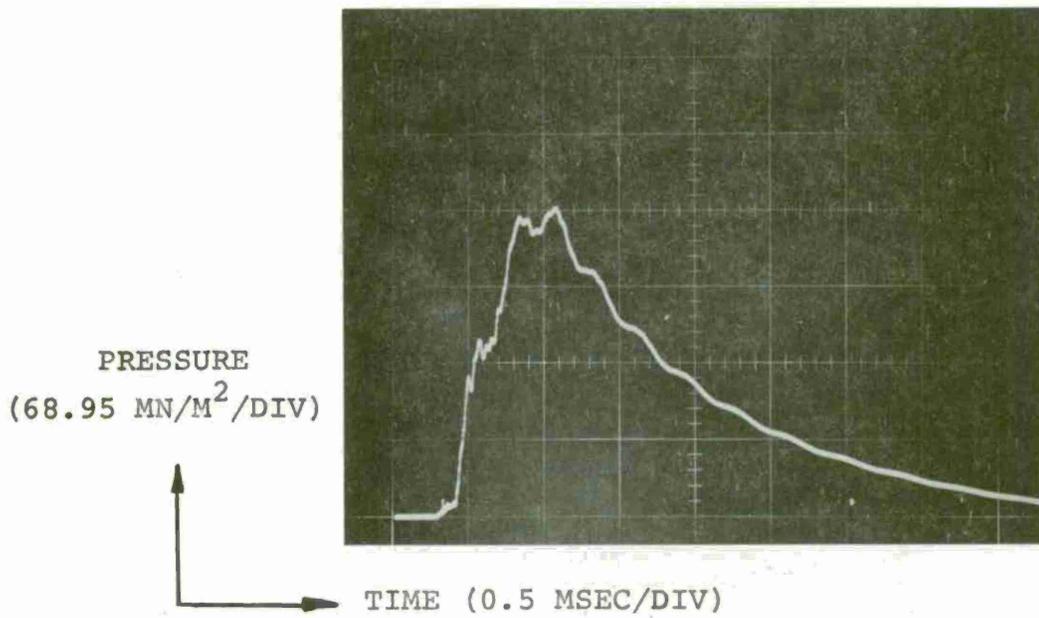
Fig. 2   Typical pressure and temperature histories of
the propellant gas in the vented-combustor
erosion apparatus.
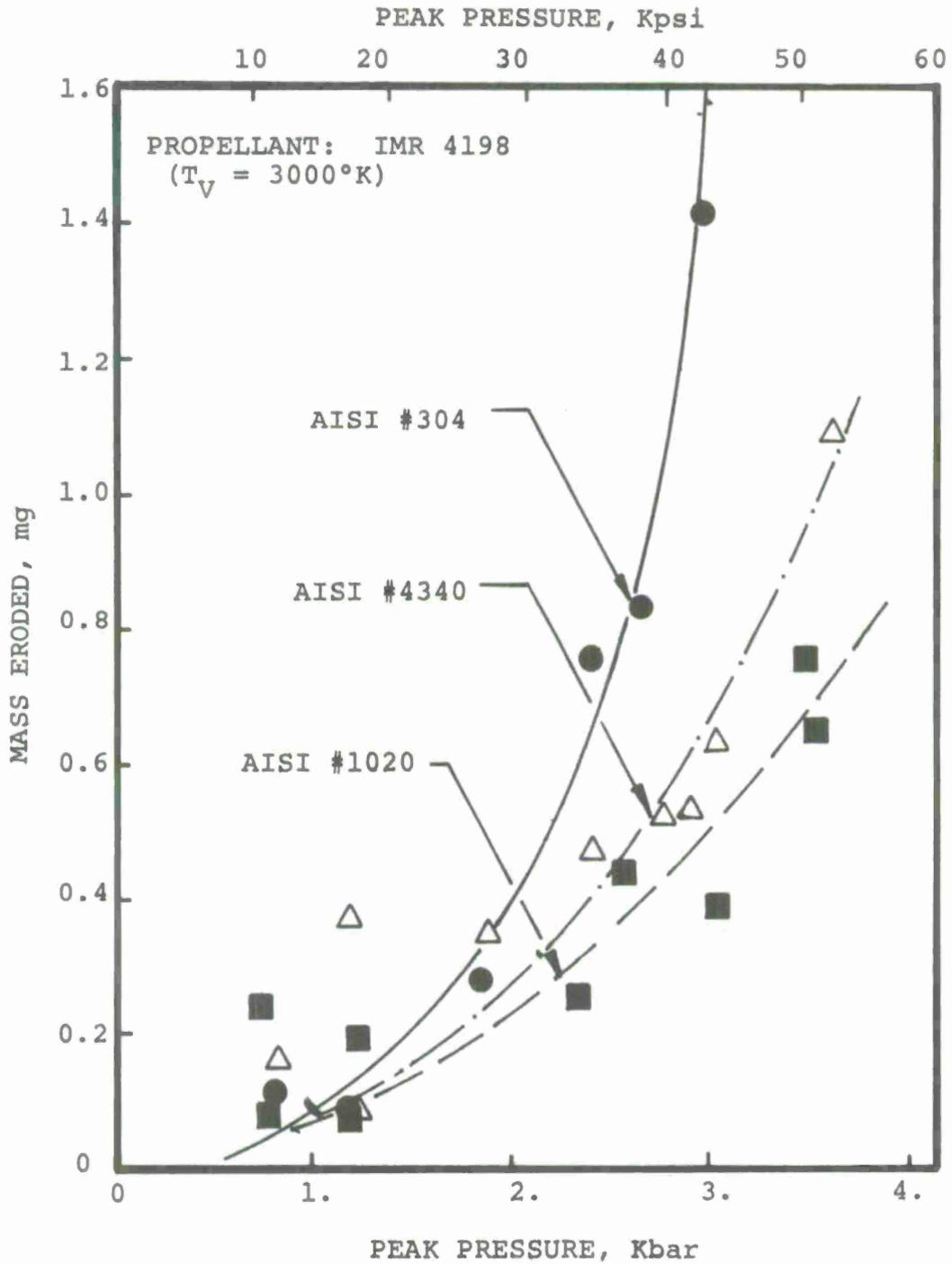
Fig. 3 Erosion results of three steel alloys, tested in the vented combustor. The AISI 304 alloy experiences the greatest erosion.
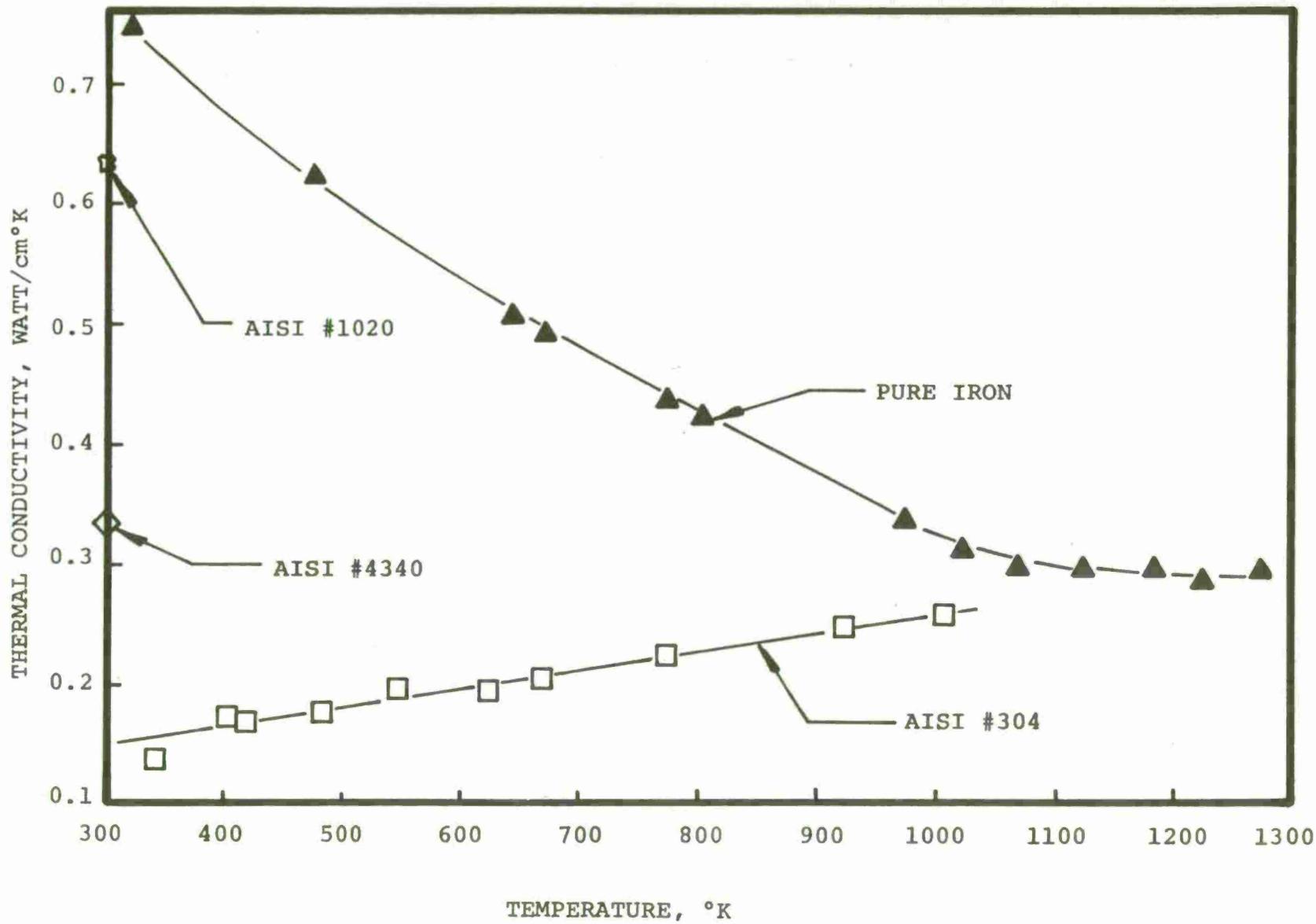
Fig. 4 Thermal conductivity of steel alloys as a function of temperature.
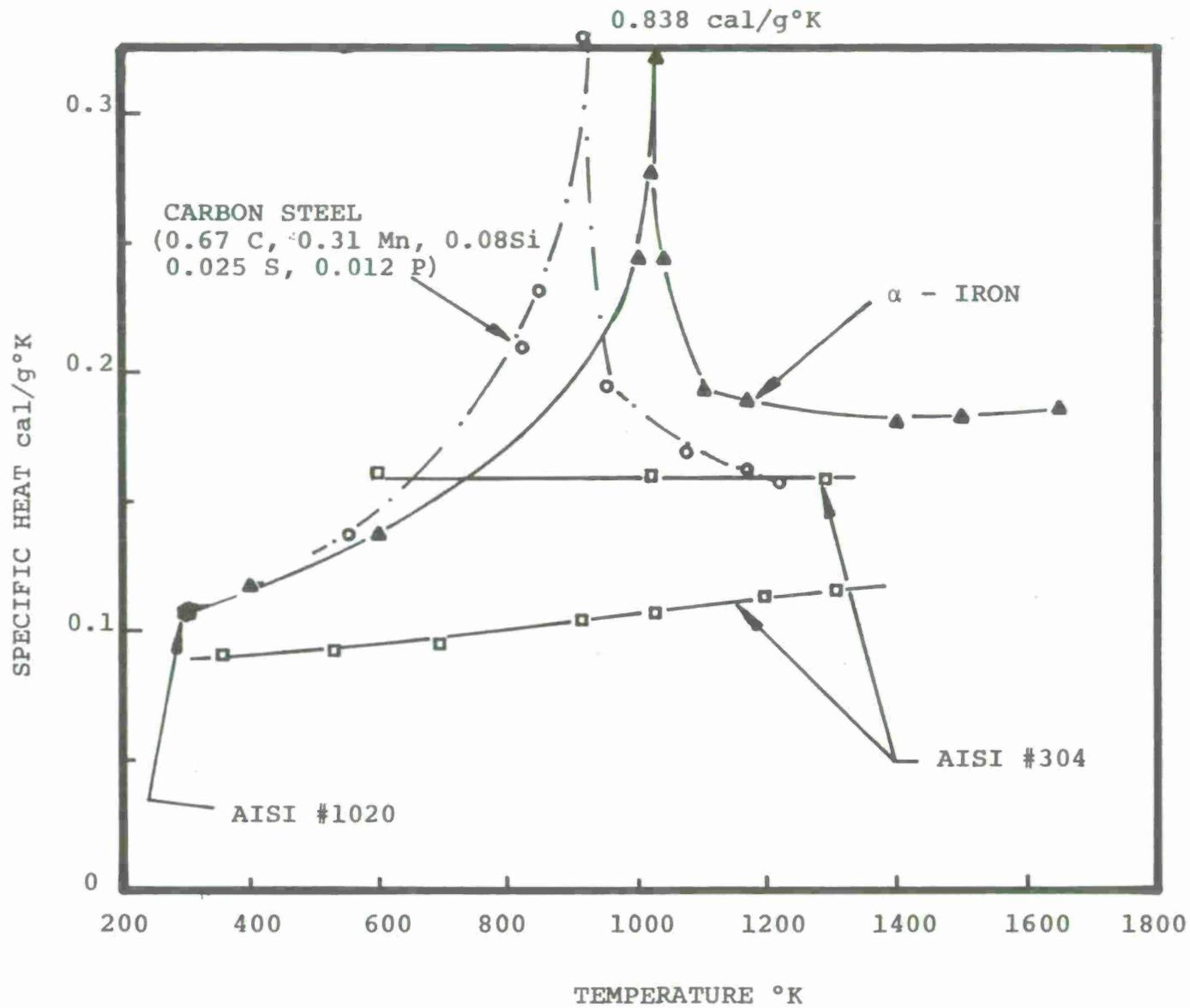
Fig. 5 Specific heat of steel alloys as a function of temperature.
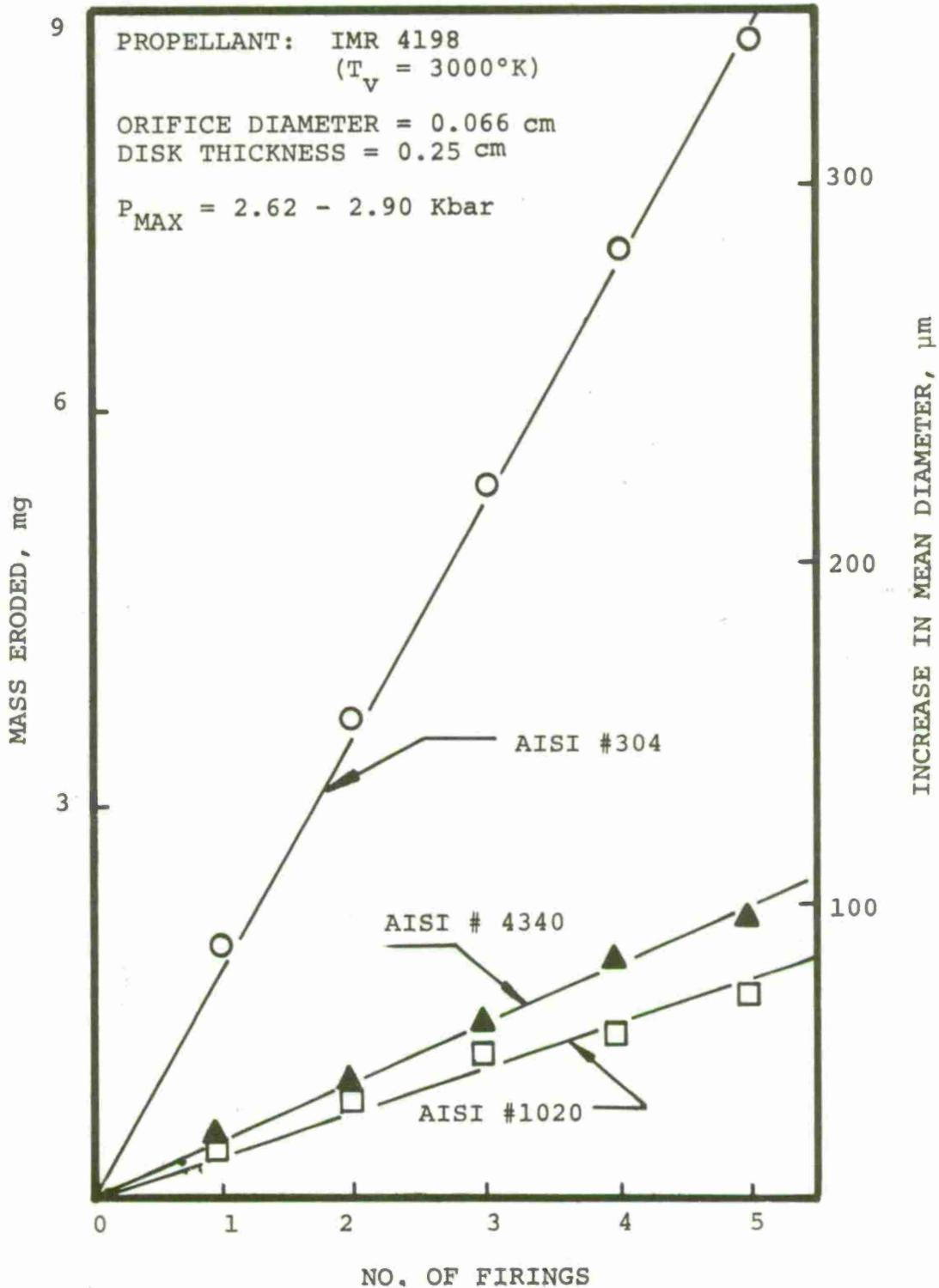
Fig. 6 Erosion of steel alloys as a function of number of firings. The linearity of the curves indicates that the mechanism of erosion does not vary from test to test. (Total number of Firings: 5)
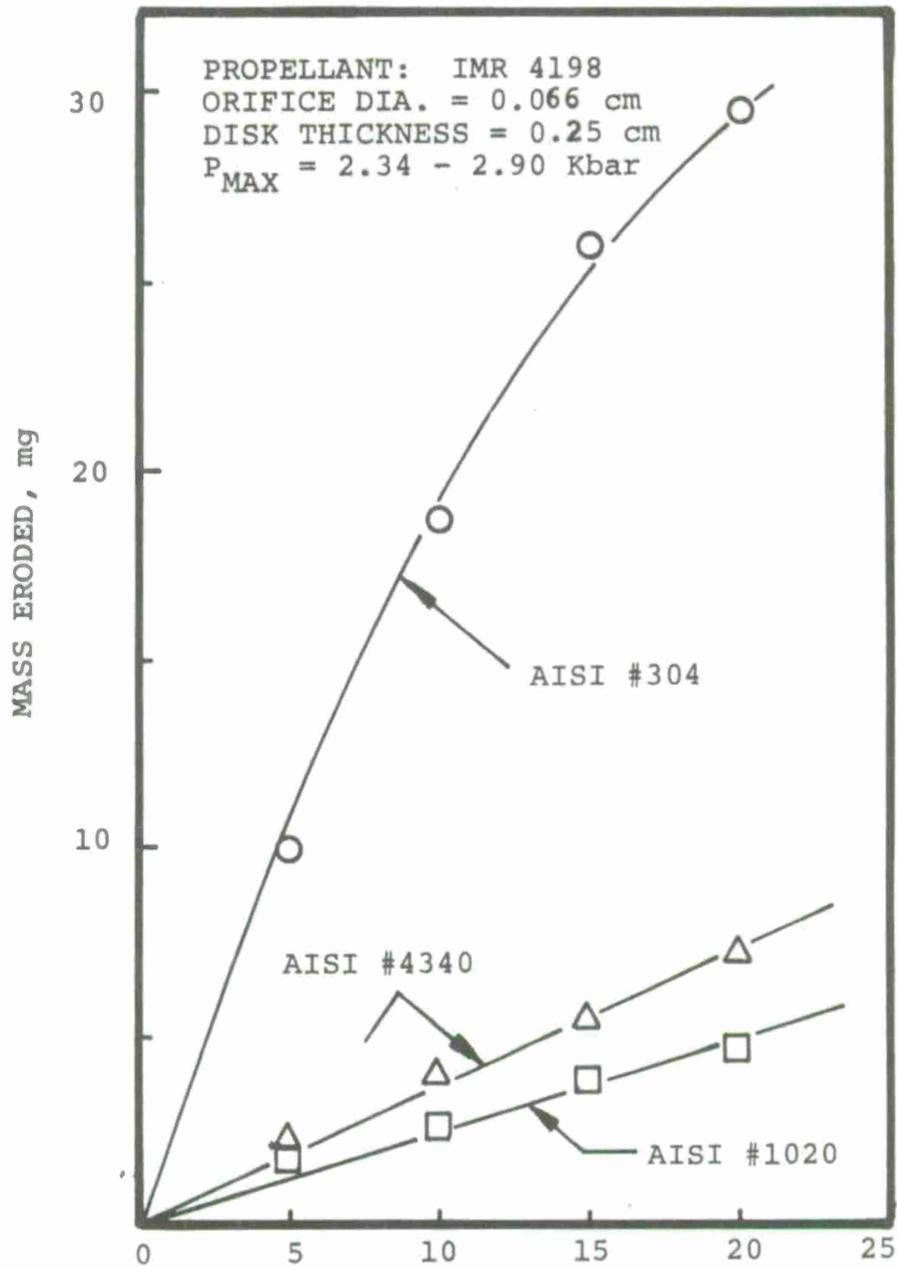
Fig. 7 Erosion of steel alloys as a function of number of firings. The linearity of the curves indicates that the mechanism of erosion does not vary from test to test. (Total Number of Firings: 20)
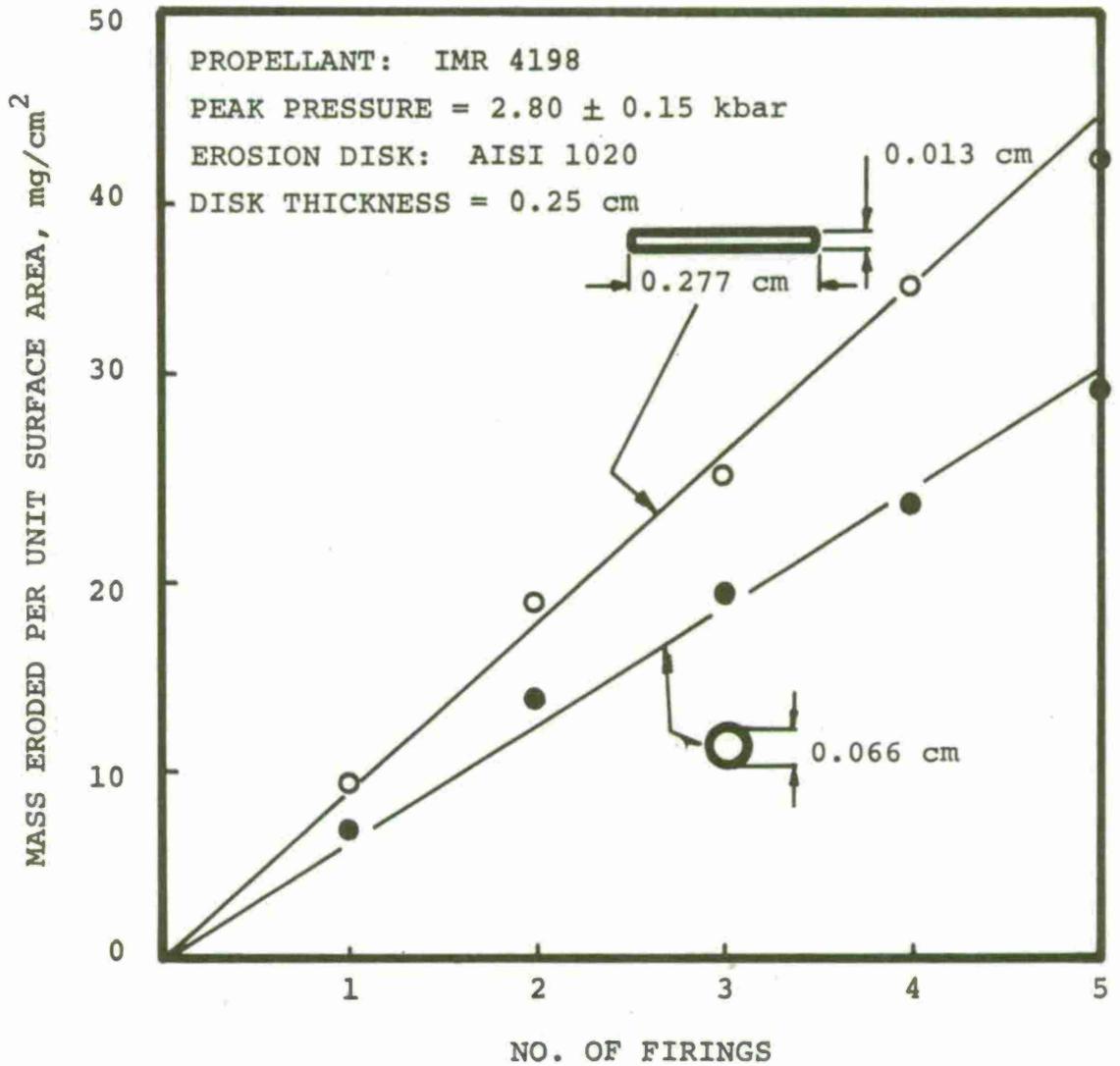
Fig. 8 Augmentation of the erosion of steel alloys using rectangular flow passage instead of cylindrical flow passage.
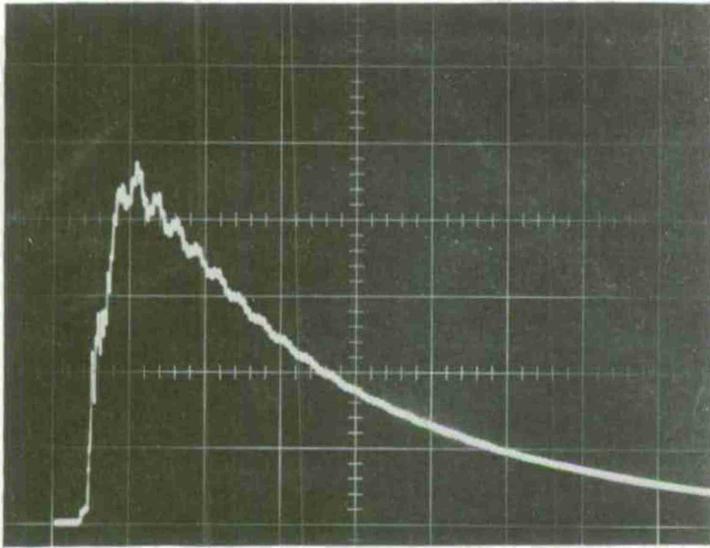
IMR 4198 PROPELLANT
T_V = 3000°K
P_{MAX} = 3.31 Kbar
$t(P_{MAX})$ = 0.75 MS
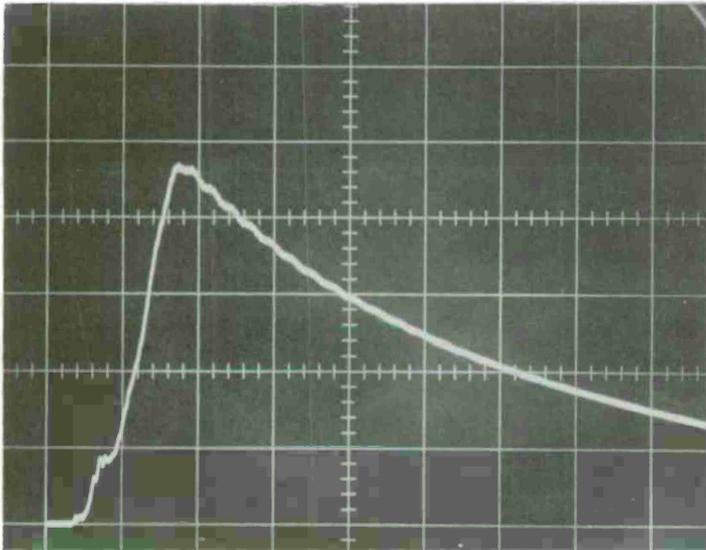
WC 846 PROPELLANT
T_V = 2840°K
P_{MAX} = 3.24 Kbar
$t(P_{MAX})$ = 1.4 MS

HORIZONTAL SCALE = 1.0 MS/DIVISION
VERTICAL SCALE   = 690 BAR/DIVISION

Fig. 9   Typical pressure traces of IMR 4198 and WC 846
          propellants showing significant difference in the
          test cycle of the erosion disk.

Fig. 10   Schematic diagram of the ballistic compressor.

The labels in the photograph read:

FINAL COMPRESSED GAS

EROSION ORIFICE

DRIVER GAS RESERVOIR

COMPRESSION TUBE

COLD GAS DRIVEN BALLISTIC COMPRESSOR (OVERALL LENGTH ≒ 10 FT)
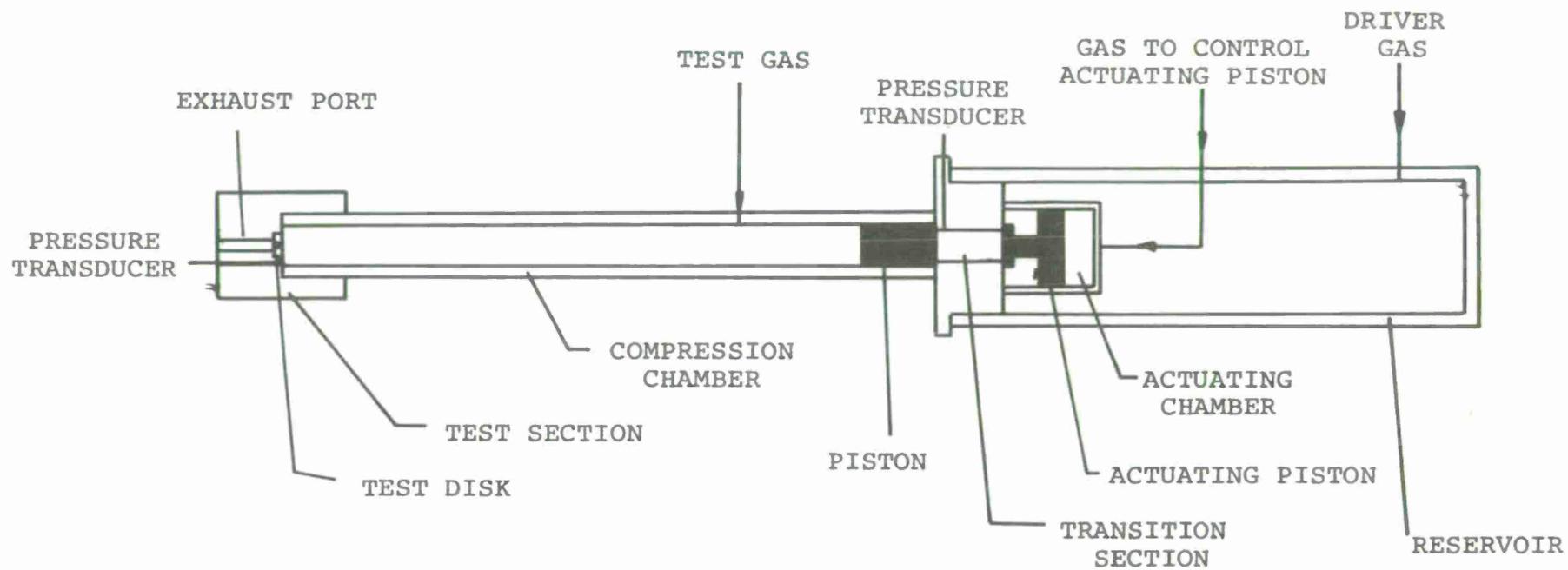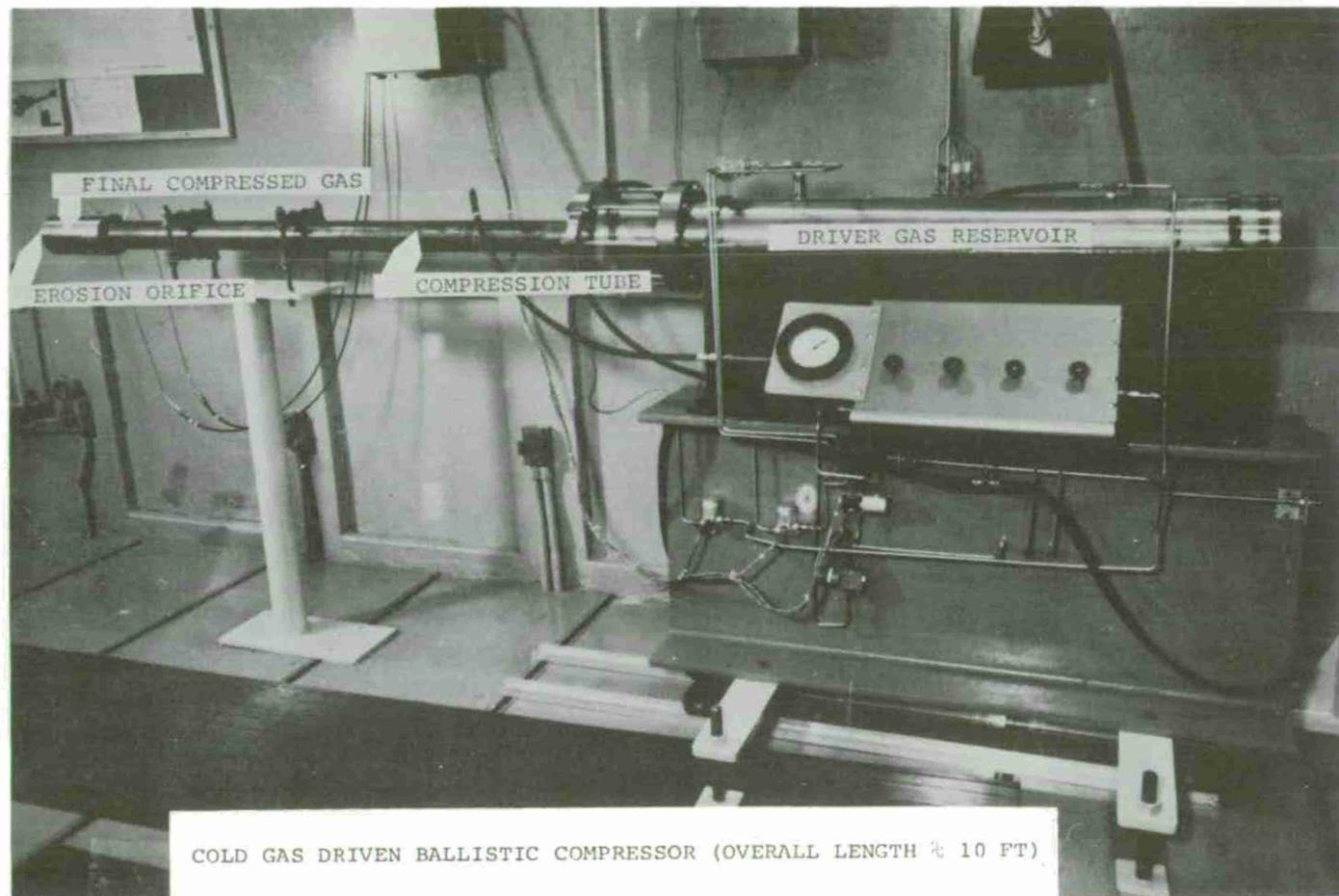
Fig. 11 Photograph of the ballistic compressor apparatus.

p_{max} = 1.4 Kbar
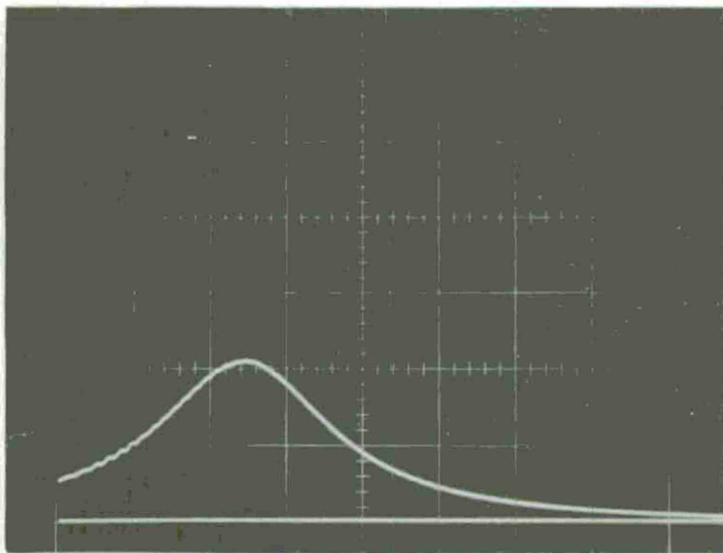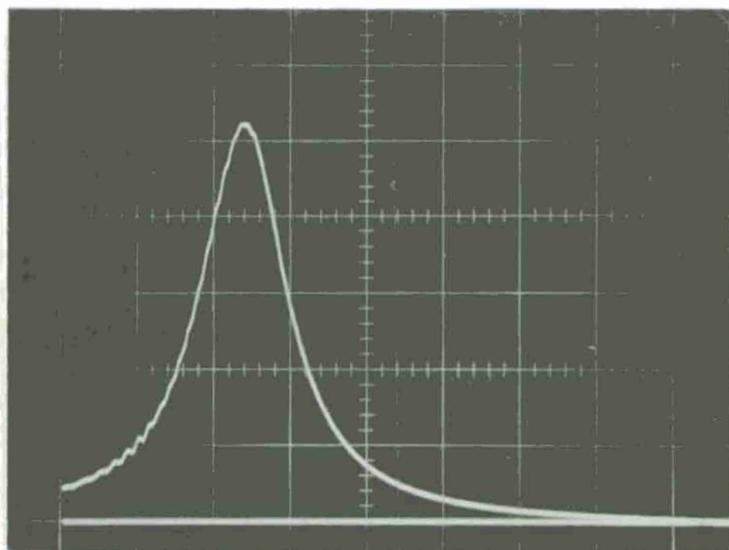
p_{max} = 3.65 Kbar

HORIZONTAL SCALE = 0.2 ms/DIVISION
VERTICAL SCALE   = 0.69 Kbar/DIVISION

TEST GAS: AIR   DRIVER GAS: AIR

Fig. 12   Typical pressure-time traces of ballistic
          compressor.
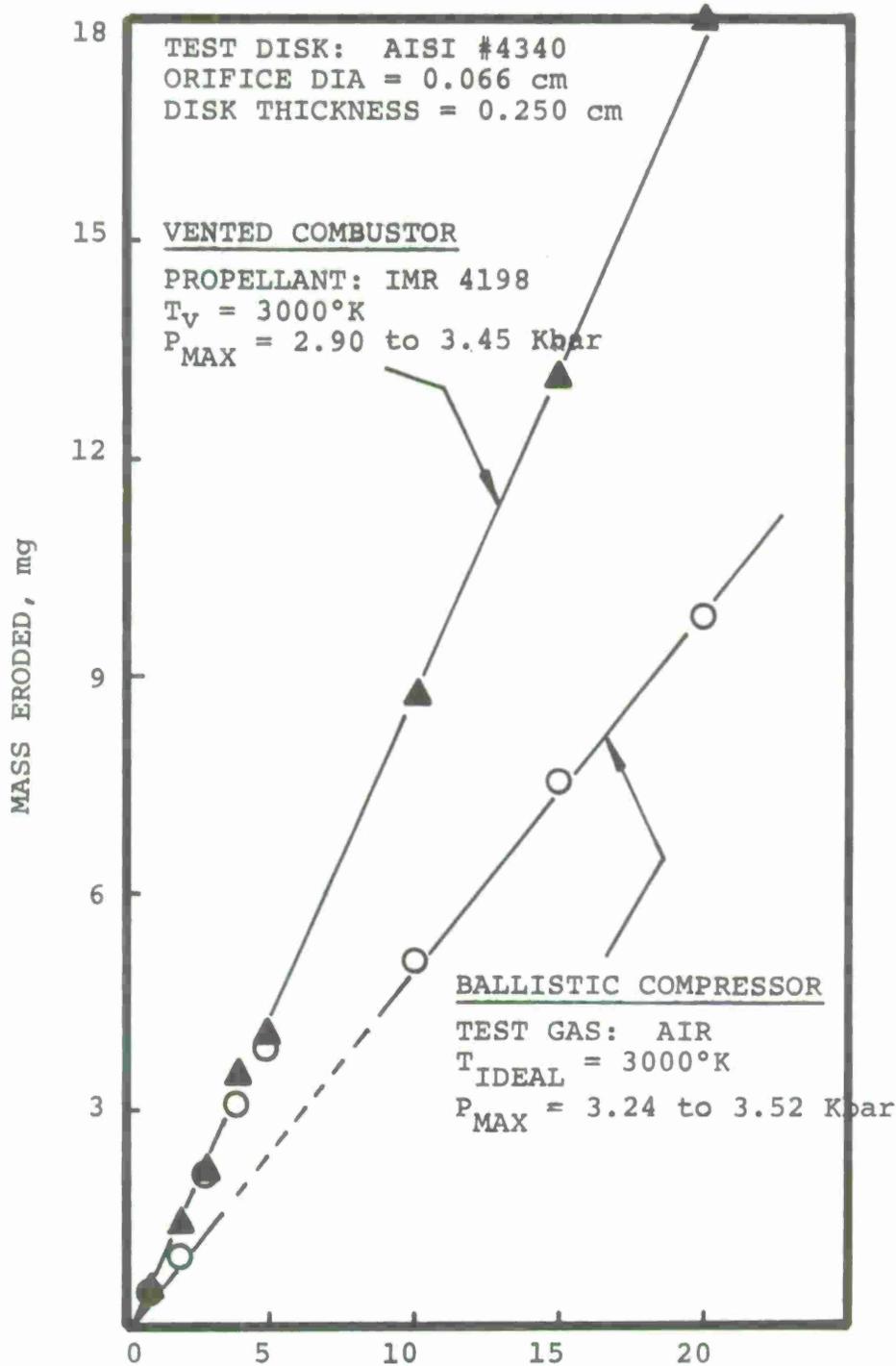
Fig. 13   Comparison of the erosion results obtained by
           the ballistic compressor and vented combustor in
           "multiple-shot" tests.

-50-
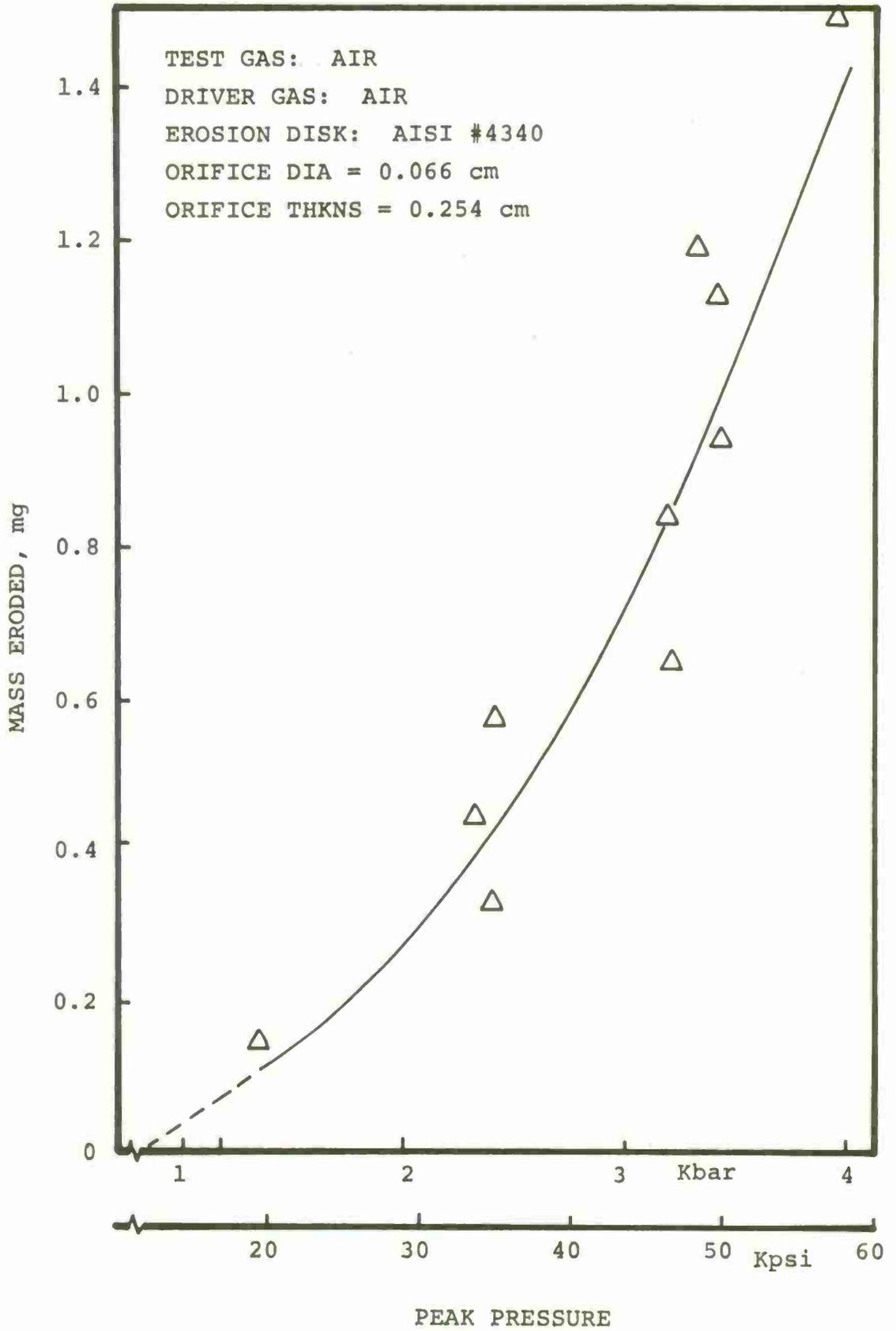
Fig. 14   Erosion of AISI #4340 as a function of the peak
           pressure generated in the ballistic compressor.
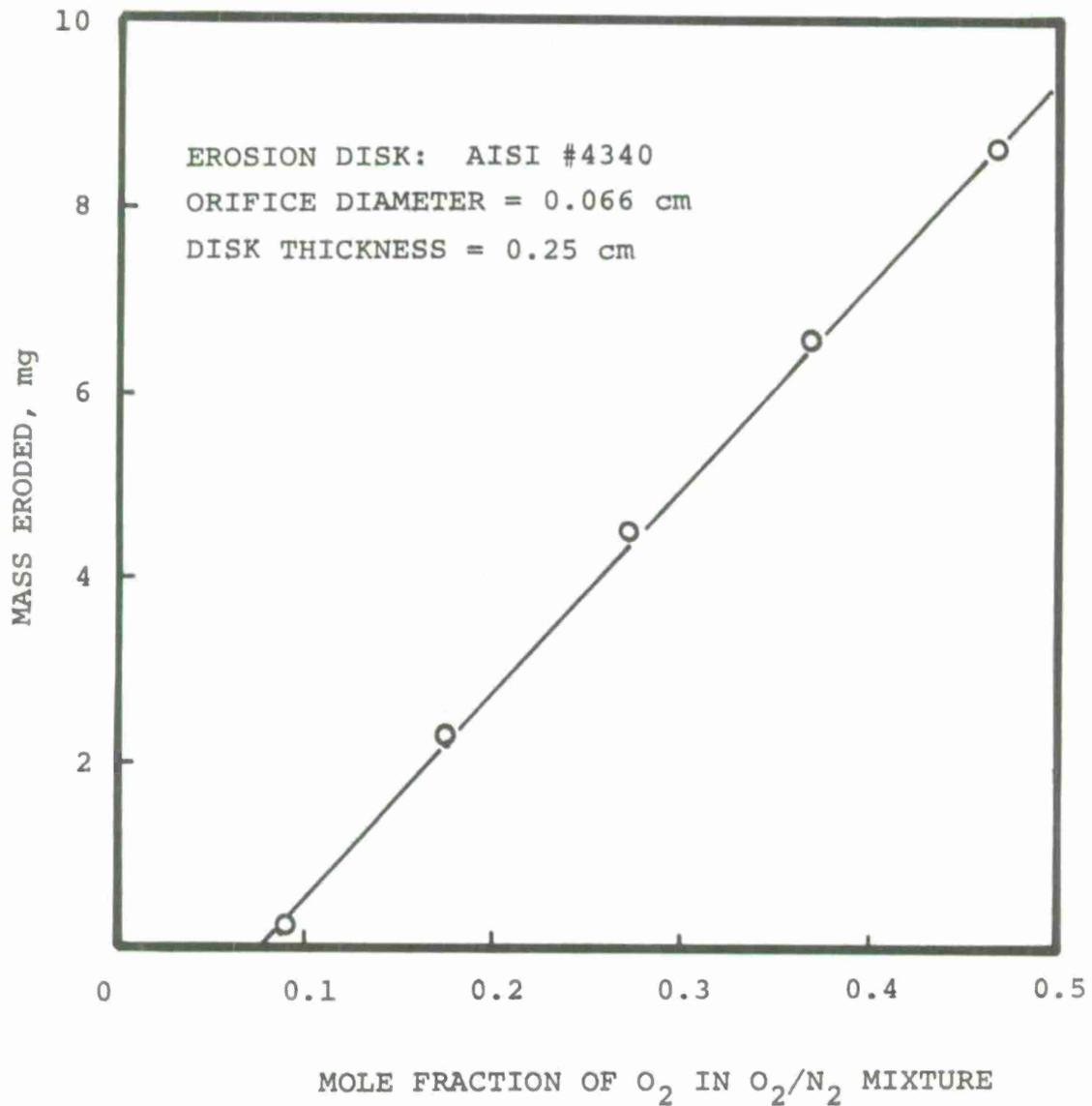
Fig. 15   Plot of mass erosion of AISI 4340 vs mole fraction of O_2 in O_2/N_2 mixture, indicating the chemical nature of erosion.

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Summerfield, Princeton University, Princeton, N.J. Perform-
ed under Contrast DAAG46-72-C-0078, Final Report, October
1975, 59 pps.

Thermal and chemical erosion characteristics of steel alloys
under the short exposure of high pressure and high tempera-
ture propellant gases (vented-combustor apparatus) and pure
gases (ballistic compressor apparatus) were studied. With
the exception of the oxygen-containing gases, (i.e.,air,O_2/
N_2 mixtures) and H_2, the mass removal experienced by steel
alloys was very small. Erosion increases linearly with the
mole fraction of O_2 in O_2/N_2 mixtures. The results clearly
demonstrate that surface reactions play a dominant role and
that the erosion is more than melting and wipe-off.